Tweaking the Dark Matter Abundance with Cosmology

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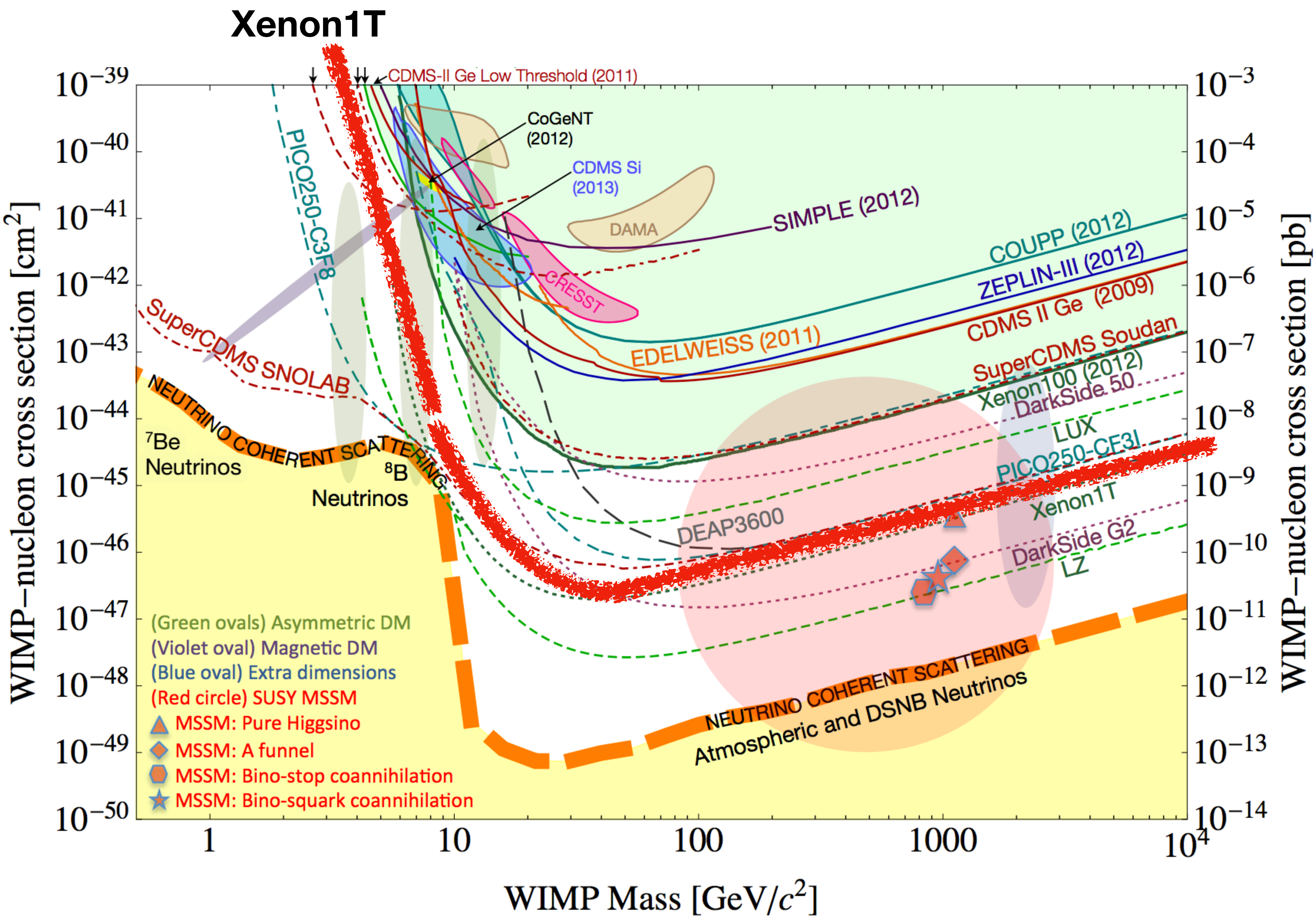
Outline

1. Diluting Dark Matter
2. Freeze-out During Matter Domination
3. Dark Matter Freeze-in
4. Freeze-in & Non-Standard Cosmology

I. Diluting Dark Matter

Current Bounds



Cosmological Impact

After dark matter is frozen out its number does not change from interactions.

$$\Omega_{\rm DM} \propto m_{\rm DM} Y_{\rm DM} \propto m_{\rm DM} \frac{n_{\rm DM}}{s}$$

However, **decaying particles** χ can heat SM bath, & **dilute $Y_{\rm DM}$** since $s \propto T^3$.

$$\Omega_{\rm DM} \propto \zeta m_{\rm DM} Y_{\rm FO}$$

Dilution factor ζ from temperature after decays $T_{\rm after}$ compared to without decays.

Giudice, Kolb, and Riotto, PRD 64 (2001) 023508
Profumo & Ullio [hep-ph/0309220].
Gelmini & Gondolo [hep-ph/0602230]
⋮
Randall, Scholtz & JU [1509.08477]
Berlin, Hooper & Krnjaic [1602.08490]
Bernal, Cosme & Tenkanen [1803.08064]
⋮

χ decay heats the bath, to $T_{\rm RH} \simeq \sqrt{M_{\rm Pl}\Gamma_\chi}$, any **frozen-out species diluted:**

$$\zeta = \left(\frac{T_{\rm without}}{T_{\rm after}}\right)^3 \sim 10^{-10}\left(\frac{T_{\rm RH}}{10~{\rm MeV}}\right)\left(\frac{10^8~{\rm GeV}}{m_\chi}\right)$$

Because of dilution, correct relic density for **weaker interactions with SM.**

Cosmological Impact

Earliest cosmological evidence

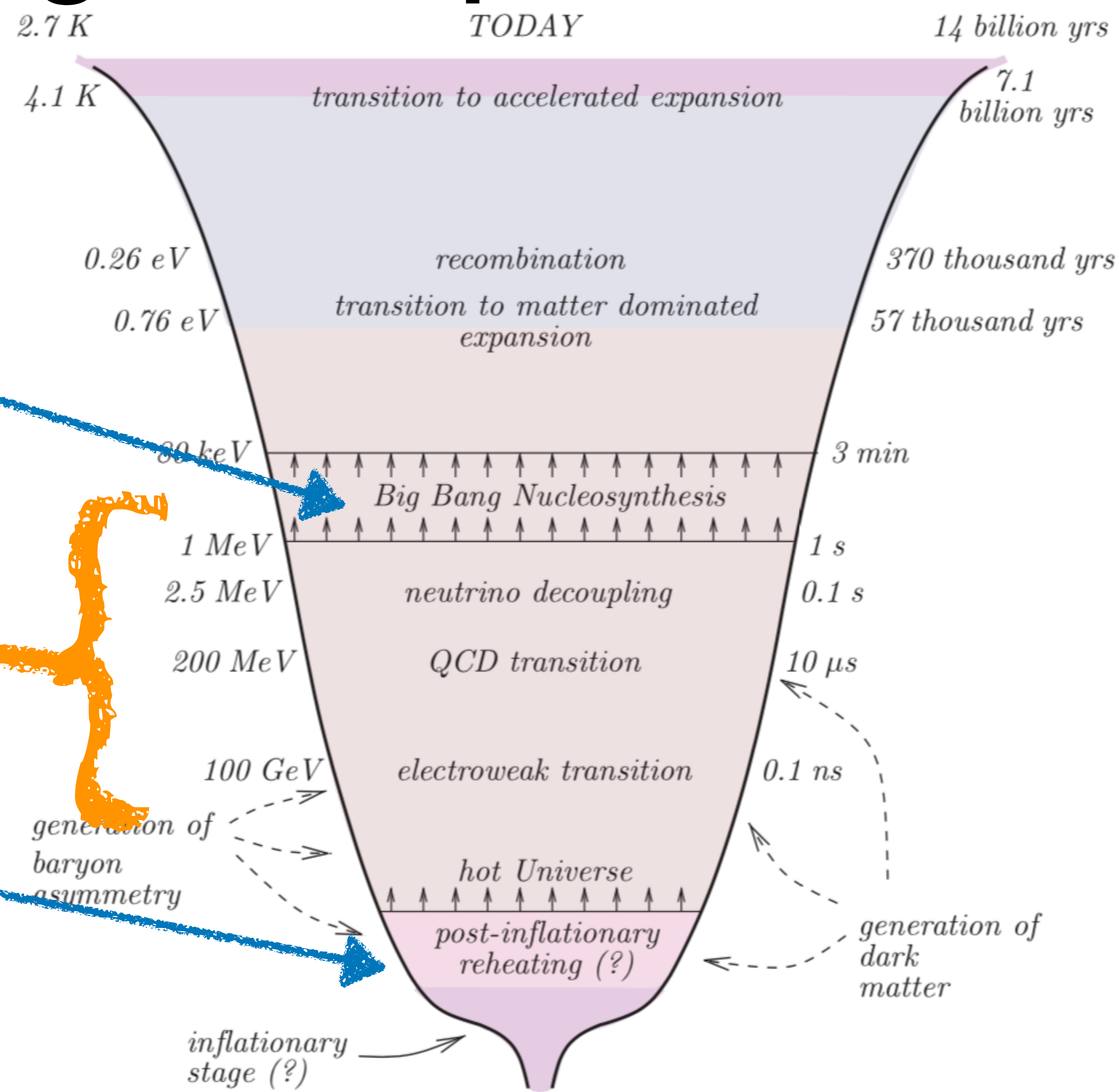
(know to be radiation dominated)

Non-Standard Model

cosmological events?

End of Inflation

(start of radiation domination?)



Changes to the Expansion Rate

Notable, expansion rate H depends critically on cosmology:

$$H \propto \begin{cases} T^2 & \text{During radiation domination} \\ T^4 & \text{During particle decays (heating)} \\ T^{3/2} & \text{During matter domination} \end{cases}$$

During particle decays (heating):

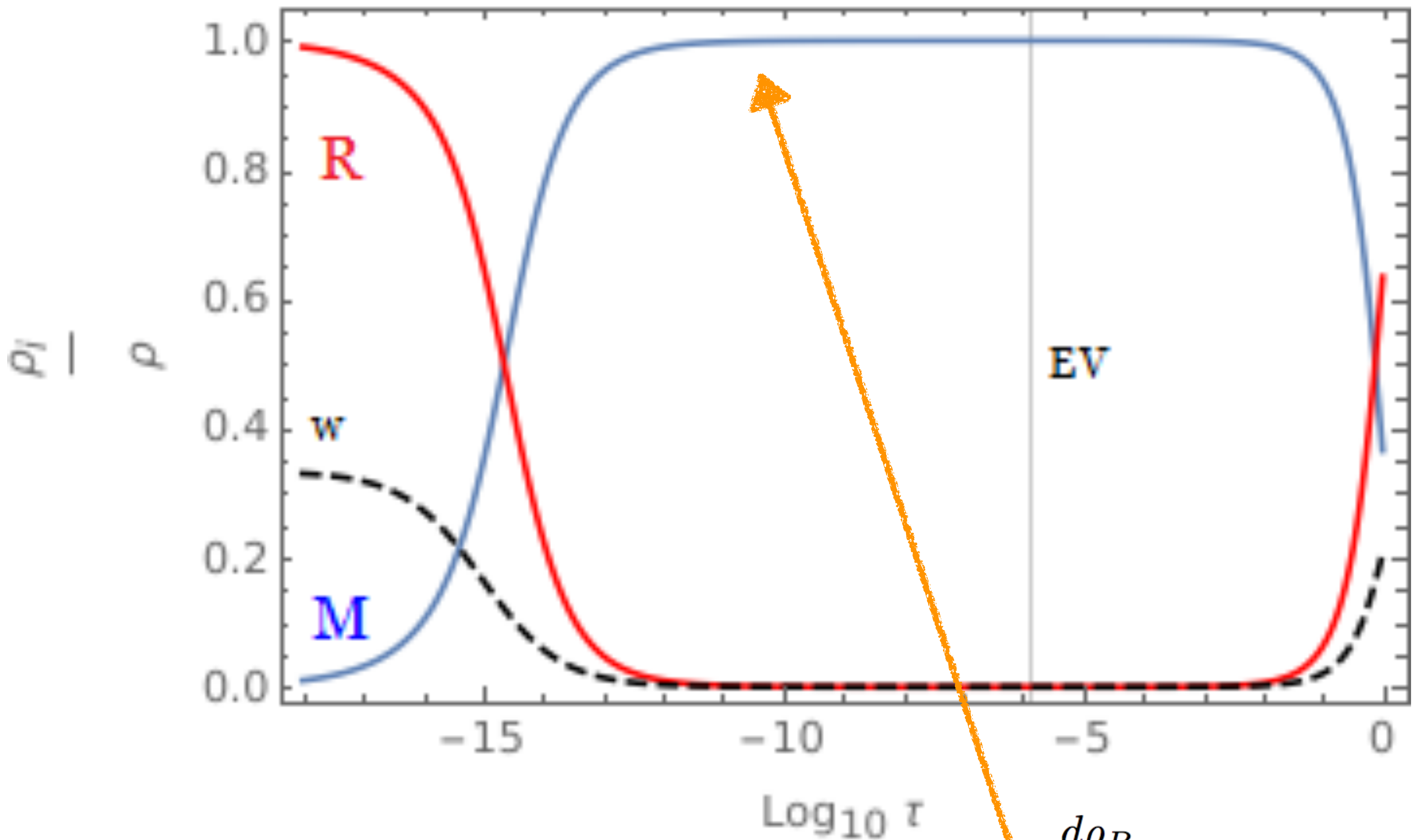
Scherrer & Turner Phys.Rev. D31 (1985) 681
Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

During matter domination:

Hamdan & JU [1710.03758]
Also (in passing): Kamionkowski & Turner PRD 42 (1990) 3310

Recall $T_{\rm FO}$ is defined $\Gamma(T_{\rm FO}) = H(T_{\rm FO})$, changing H impacts final $Y_{\rm DM}$.

Decays vs Matter Domination

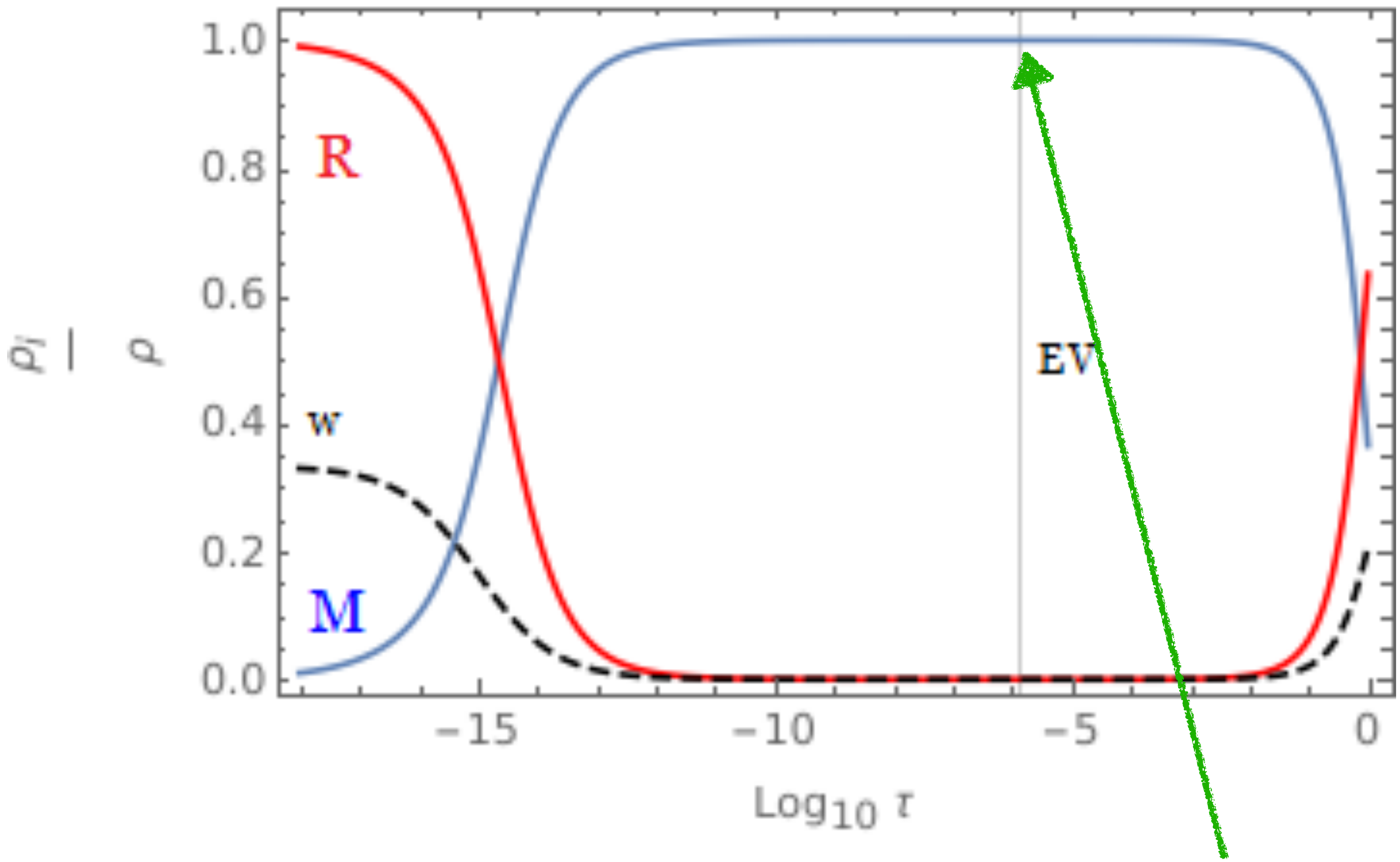


Matter Domination:

$$\frac{d\rho_R}{dt} = -4H\rho_R + \langle\sigma v\rangle 2\langle E_X\rangle \left[n_X^2 - (n_X^{eq})^2\right]$$

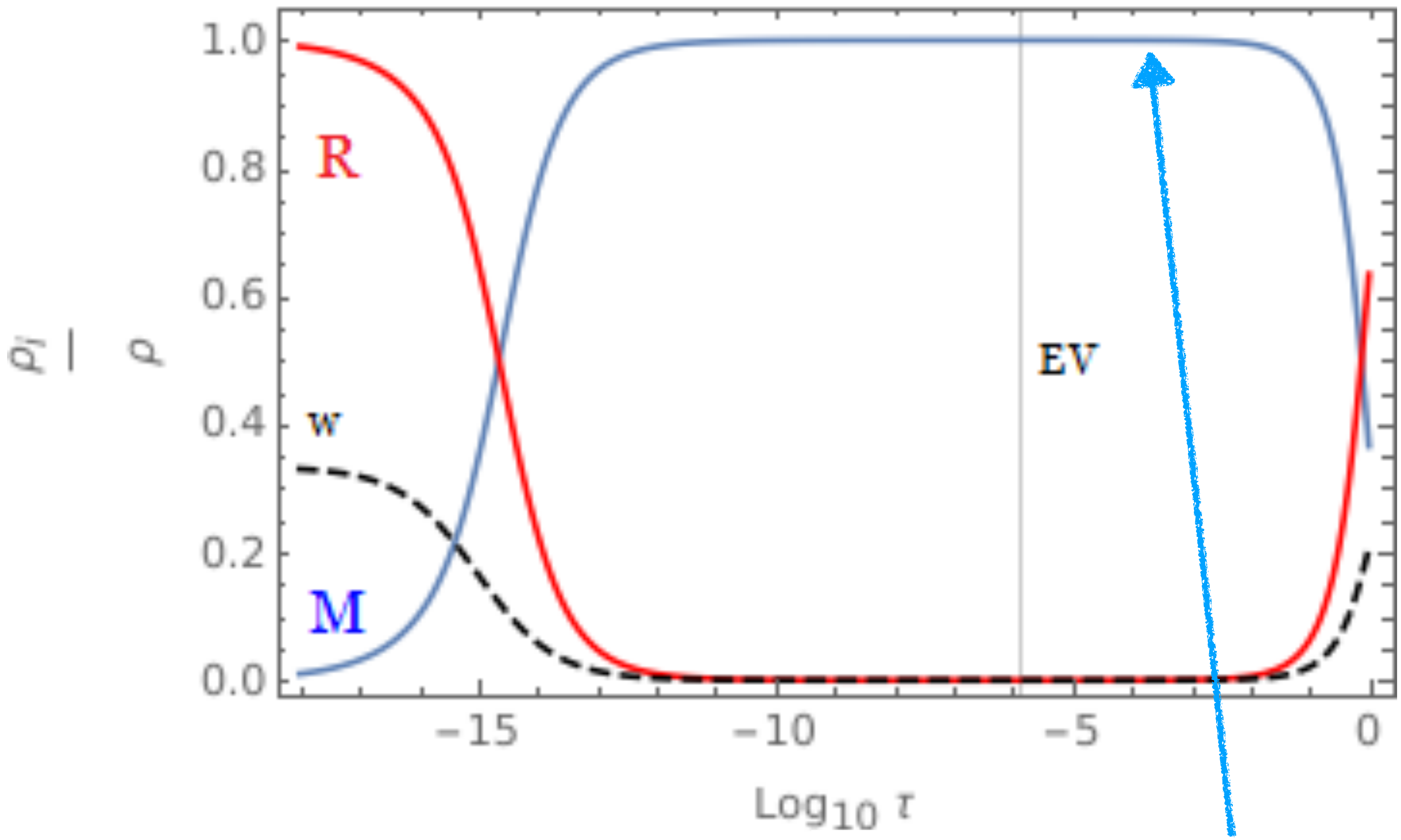
$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle \left[n_X^2 - (n_X^{eq})^2\right] \; .$$

Decays vs Matter Domination



Point of non-negligible entropy production in bath.

Decays vs Matter Domination



Decay Regime:

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi \rho_\phi + \langle \sigma v \rangle 2 \langle E_X \rangle \left[n_X^2 - (n_X^{eq})^2 \right]$$

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[n_X^2 - (n_X^{eq})^2 \right] .$$

Giudice, Kolb, & Riotto, PRD 64 (2001) 023508

II. Freeze-out During Matter Domination

Changes to the Expansion Rate

Notable, expansion rate H depends critically on cosmology:

$$H \propto \begin{cases} T^2 & \text{During radiation domination} \\ T^4 & \text{During particle decays (heating)} \\ T^{3/2} & \text{During matter domination} \end{cases}$$

Giudice, Kolb, and Riotto, PRD 64 (2001) 023508 (during particle decays)

Hamdan & JU [1710.03758] (during matter domination)

Also (in passing): Kamionkowski & Turner PRD 42 (1990) 3310

Recall $T_{\rm FO}$ is defined $\Gamma(T_{\rm FO}) = H(T_{\rm FO})$, changing H impacts final $Y_{\rm DM}$.

Matter Dominated Freeze-out

One can **emulate** the standard Boltzmann treatment

$$\dot{n}_X + 3Hn_X = -\langle\sigma v\rangle[n_X^2 - (n_X^{\rm eq})^2]$$

but with different form for H

$$H \simeq H_\star \left(\frac{g_*(T)}{g_*(T_\star)}\right)^{3/8} \left(\frac{T}{T_\star}\right)^{3/2} \left[(1-r) + r\left(\frac{T}{T_\star}\right)\right]^{1/2} \quad \text{for} \quad r = \begin{cases} 1 & \text{RD} \\ 0 & \text{MD} \end{cases}$$

Where $T_\star$ is temperature χ becomes matter-like and $H_\star \equiv H(T_\star)$

Radiation dominated freeze-out

$$T_{\rm FO}^{\rm RD} \simeq \frac{m_{\rm DM}}{\ln\left[m_{\rm DM} M_{\rm Pl}\sigma_0\right]}$$

$$Y_{\rm FO}^{\rm RD} = 3\sqrt{\frac{5}{\pi}}\frac{\sqrt{g_\star}}{g_{\star S}}\frac{(n+1)x_F^{n+1}}{M_{\rm pl} m_{\rm DM}\sigma_0}$$

Scherrer and Turner, PRD 33 (1986) 1585

Matter dominated freeze-out

$$T_{\rm FO}^{\rm MD} \simeq \frac{m_{\rm DM}}{\ln\left[m_{\rm DM}^{3/2} M_{\rm Pl}\sigma_0/\sqrt{T_\star}\right]}$$

$$Y_{\rm FO}^{\rm MD} = 3\sqrt{\frac{5}{\pi}}\frac{\sqrt{g_*}}{g_{*S}}\frac{(n+3/2)x_F^{n+3/2}}{M_{\rm Pl} m_X \sigma_0 \sqrt{x_\star}} .$$

Hamdan & JU [1710.03758]

Matter Dominated Freeze-out

$Y_{\rm DM}$ in matter dominated FO **different to radiation dominated** case.

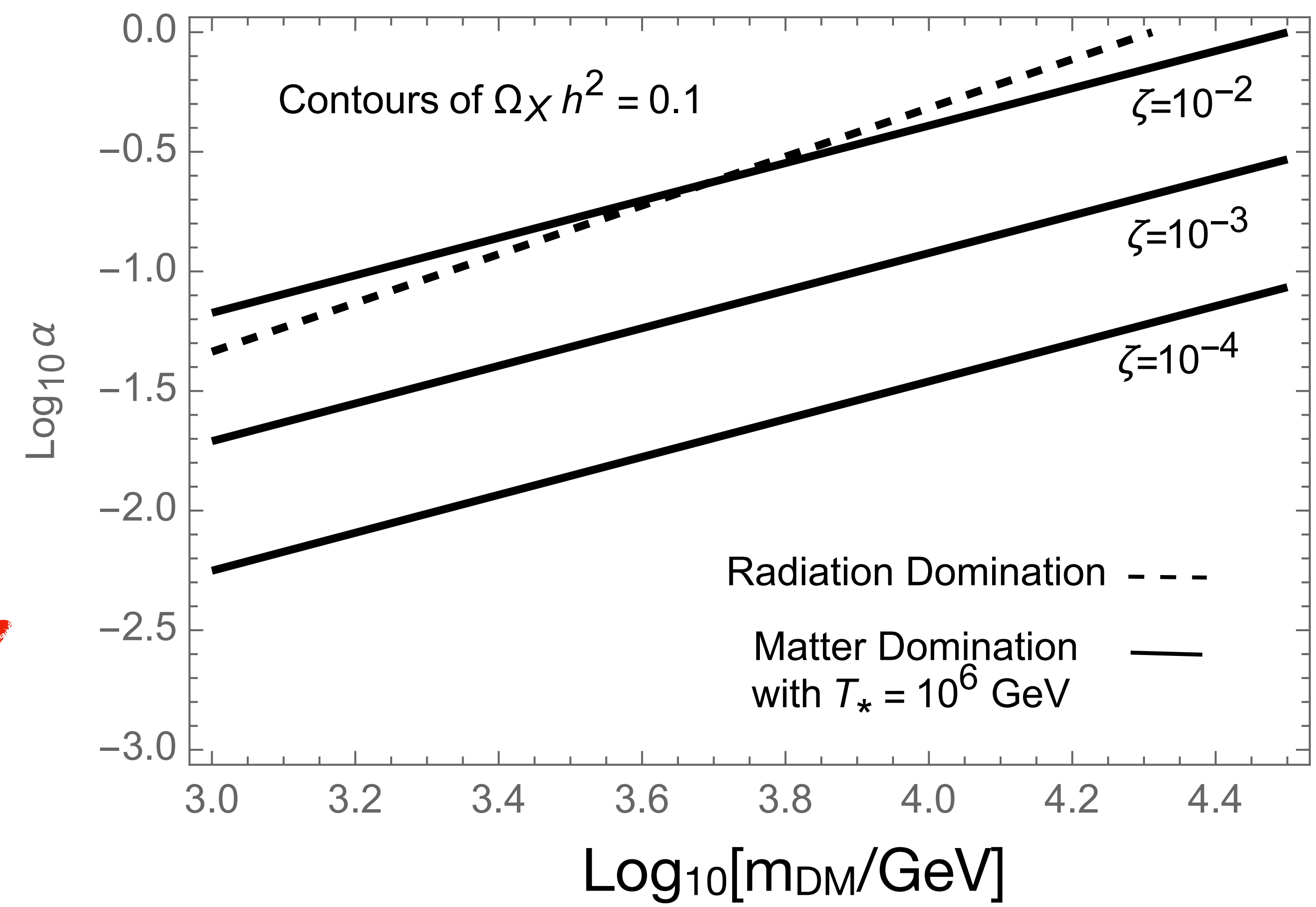
Radiation domination restored after freeze-out as **"matter" decays** to SM.

Required because **observations imply** radiation domination prior to current epoch.

This **leads to dilution ζ** of the dark matter abundance:

$$\Omega_{\rm DM} = \zeta \times \frac{s_0 m_X Y_{\rm FO}}{\rho_c}$$

More dilution implies smaller couplings



Weakening search limits compared to radiation dominated FO.

Hamdan & JU [1710.03758]

Matter Dominated Freeze-out

For DM freeze-out **during matter domination**, whilst avoiding cosmological constraints:

a). Universe **matter dominated** during freeze-out

b). Matter domination ends after dark matter freeze-out

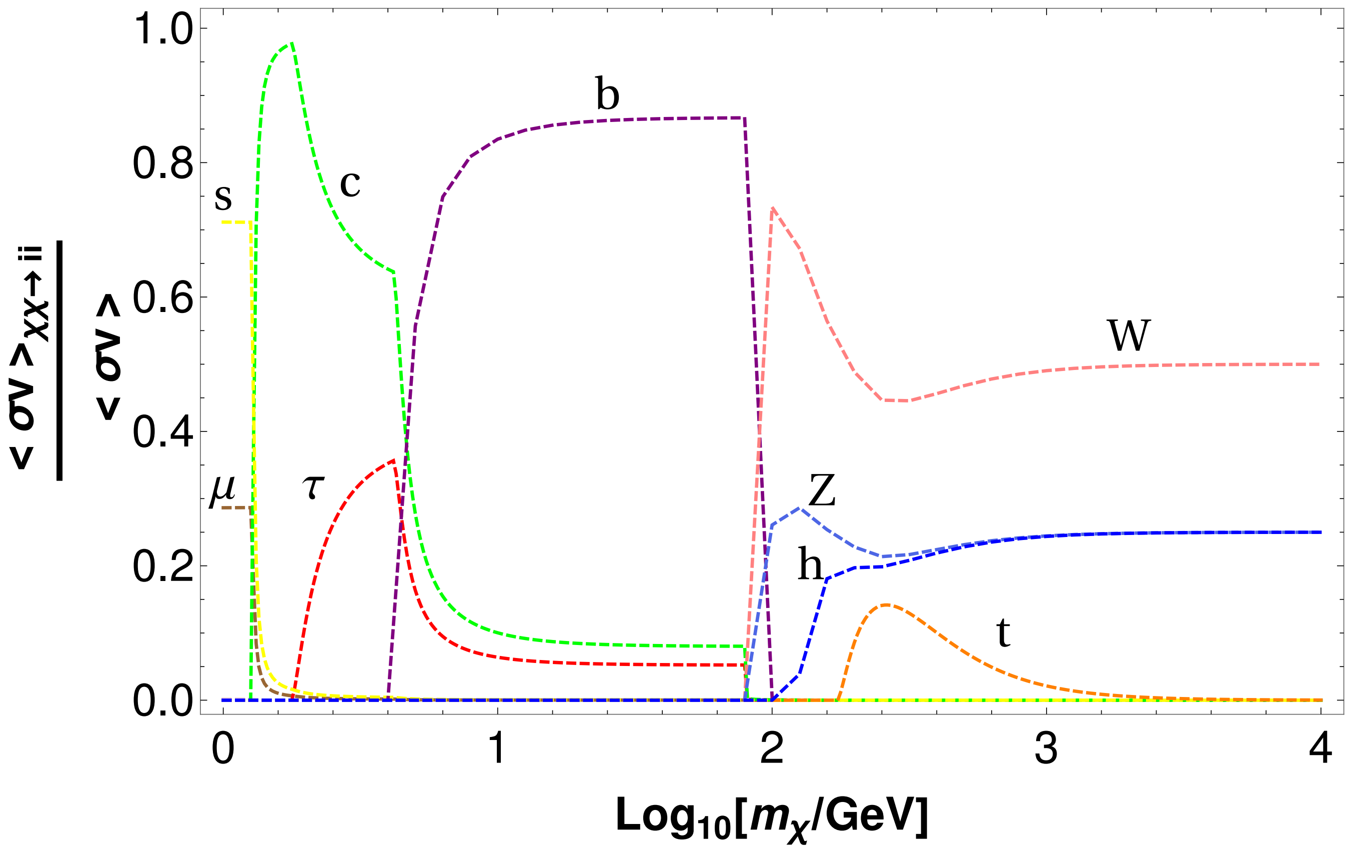
c). Reheat temperature above few MeV for **BBN**

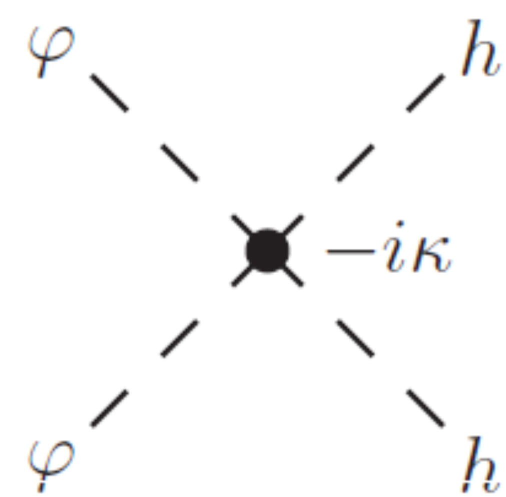
d). ϕ **decays negligible** during dark matter freeze-out

o.w./ similar to Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

e). **Cold** dark matter: $x_f > 3$

Application: Scalar Higgs Portal

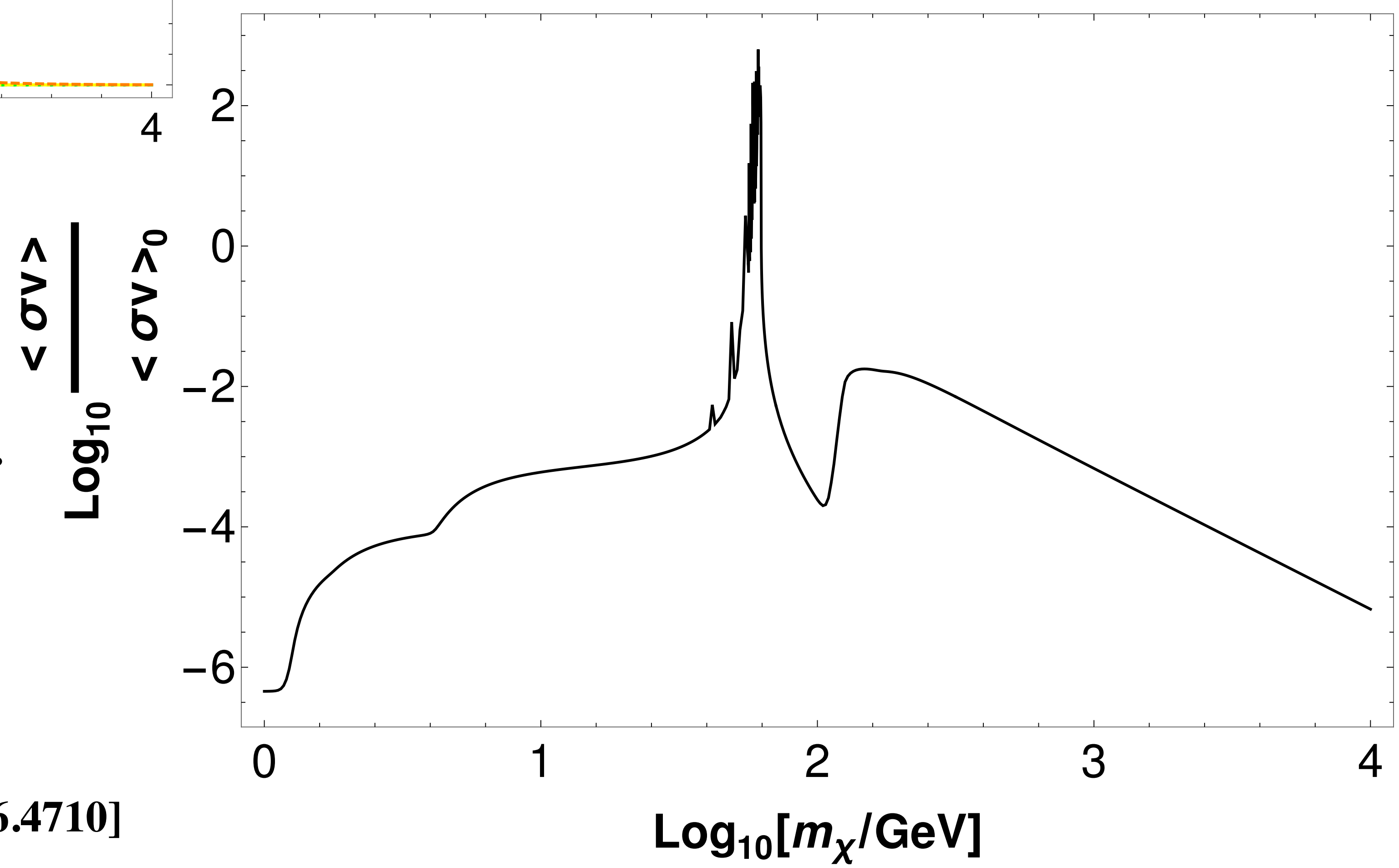




Annihilation cross section

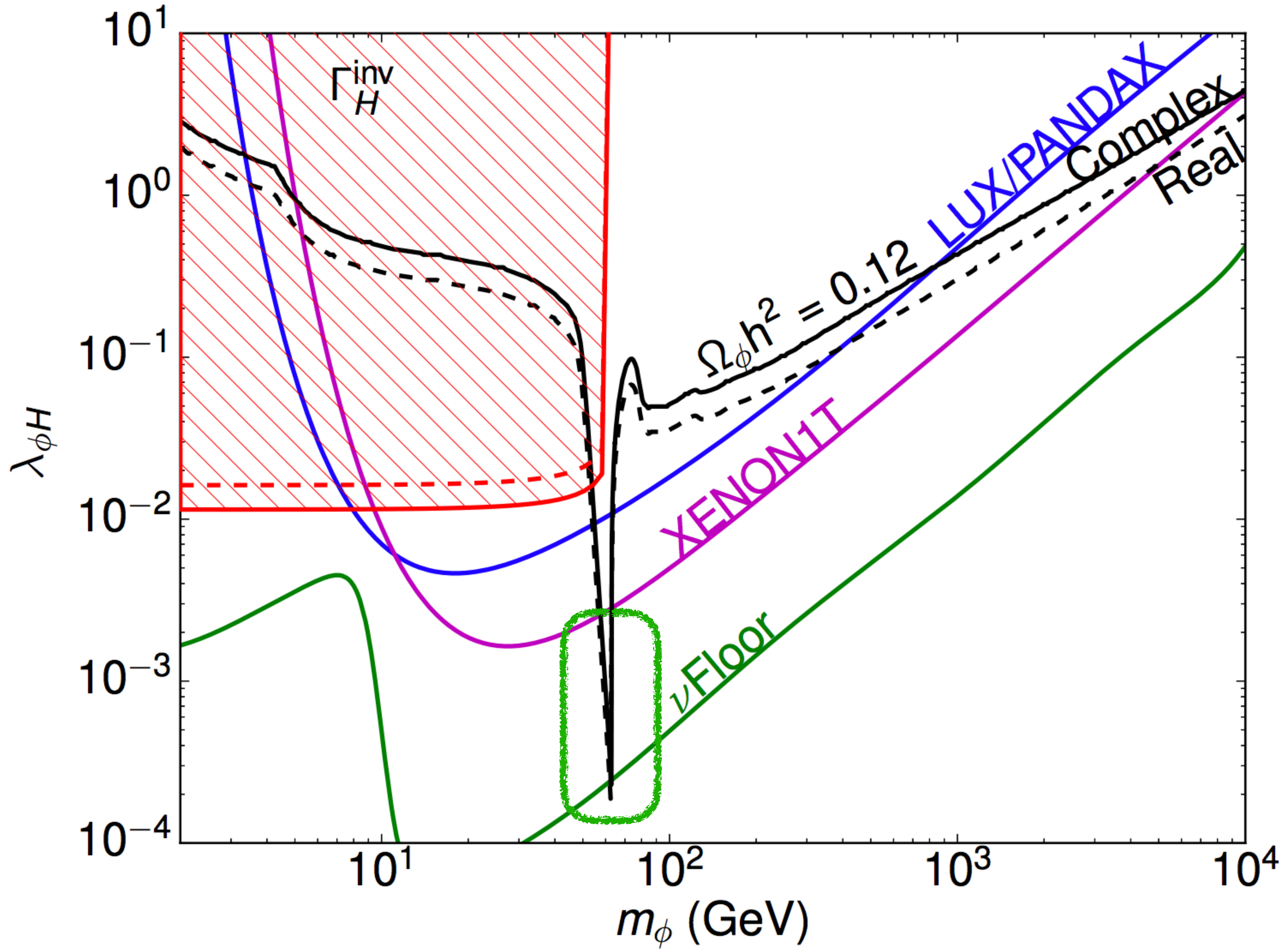
units of thermal relic cross section.

$$\langle\sigma v\rangle_0 = 3\times10^{-26}\text{cm}^3/\text{s}$$



Classic Ref: Cline, Kainulainen, Scott, Weniger [1306.4710]

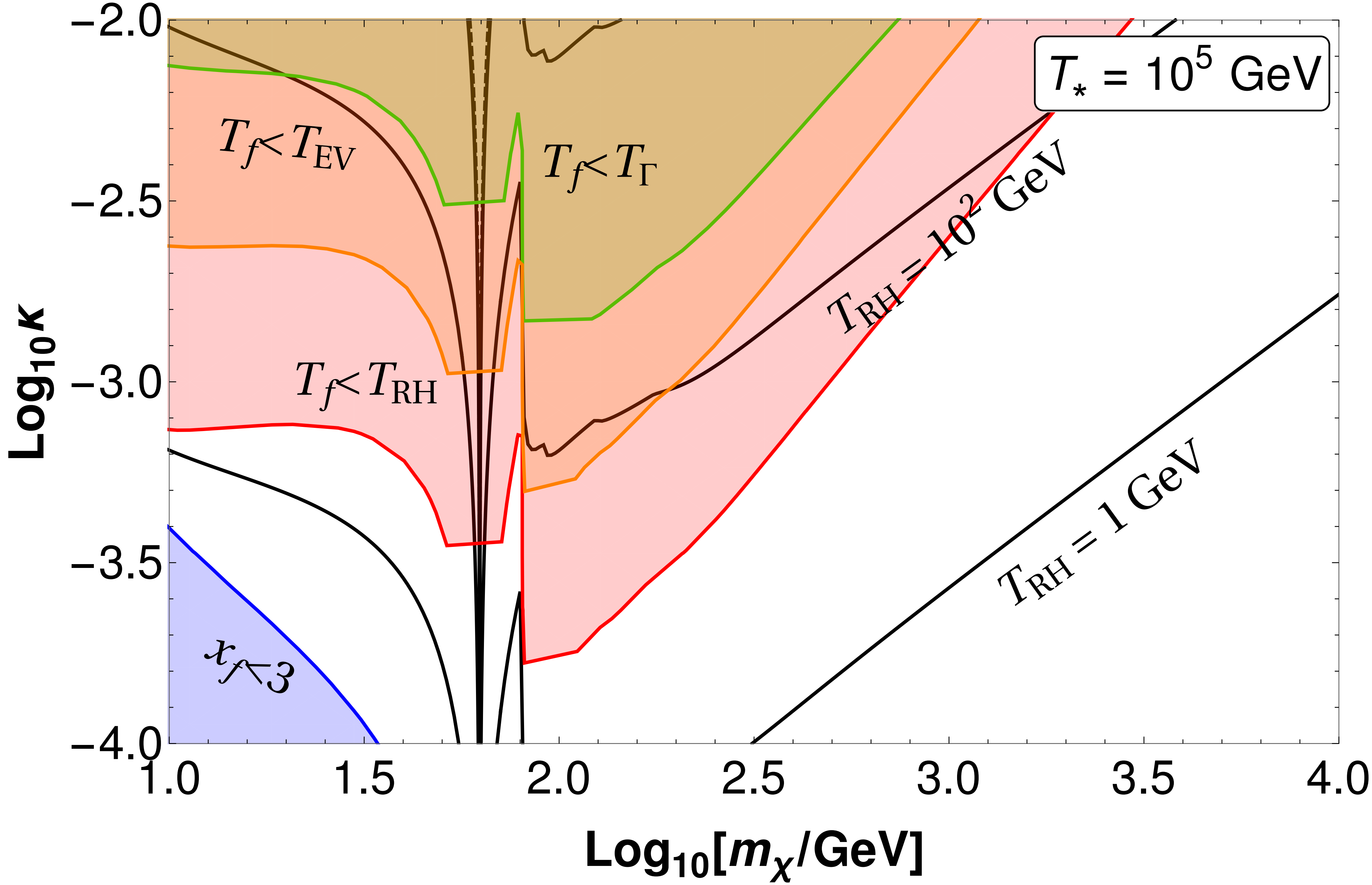
Application: Scalar Higgs Portal



Scalar Higgs Portal assuming Standard Cosmology is **experimentally excluded** away from region of resonant annihilation via the Higgs.

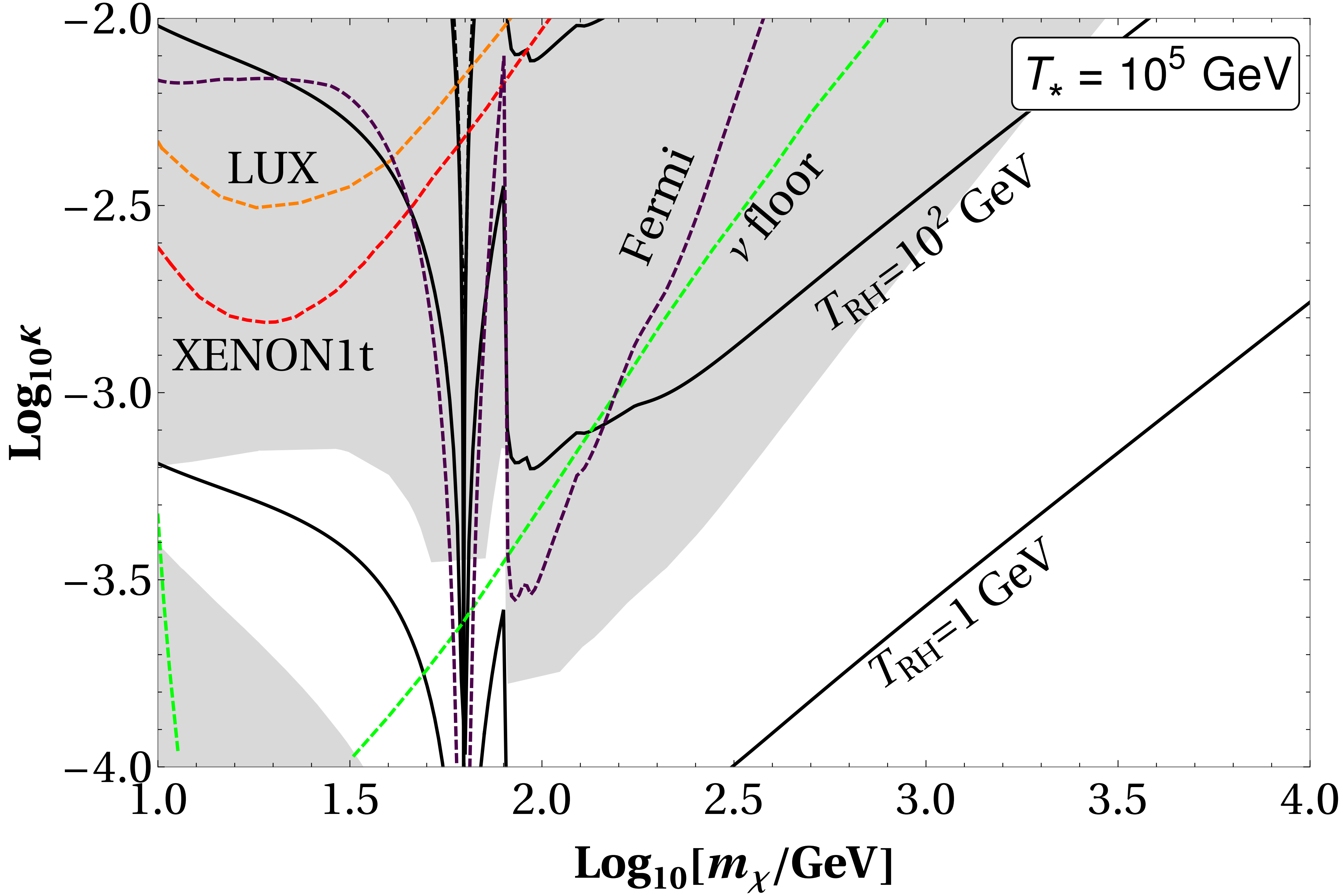
Escudero-Berlin-Hooper-Lin [1609.09079]

MDFO via Scalar Higgs Portal



Hamdan, Thesis 2018 & Chanda, Hamdan, & JU [1910.02616]

MDFO via Scalar Higgs Portal

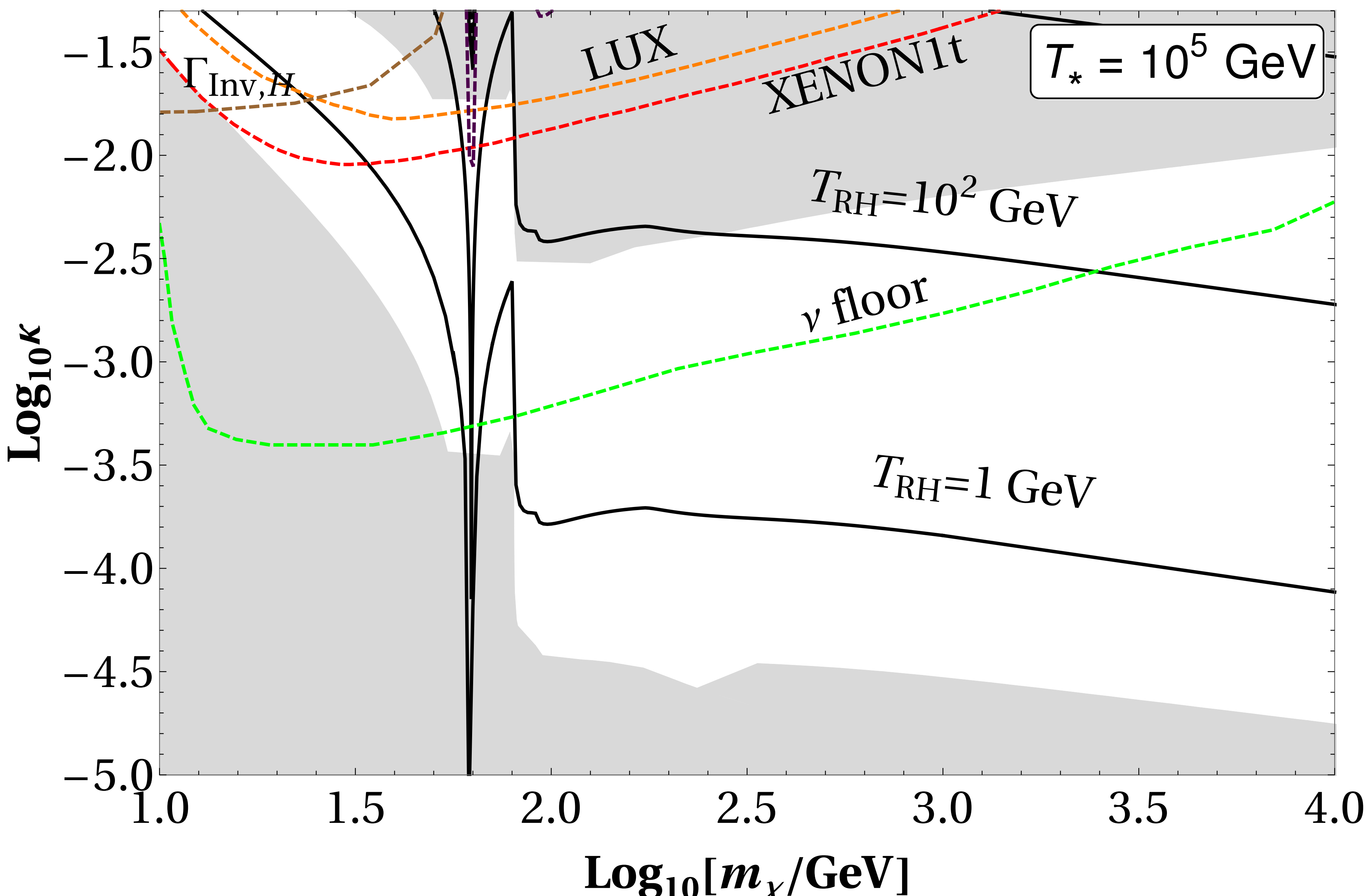


In MDFO classic **Higgs Portal revived** as a viable model.

Hamdan, Thesis 2018 & Chanda-Hamdan-JU [1910.today]
See also: Bernal, Cosme & Tenkanen [1803.08064], Hardy [1804.06783]

MDFO via Fermion Higgs Portal

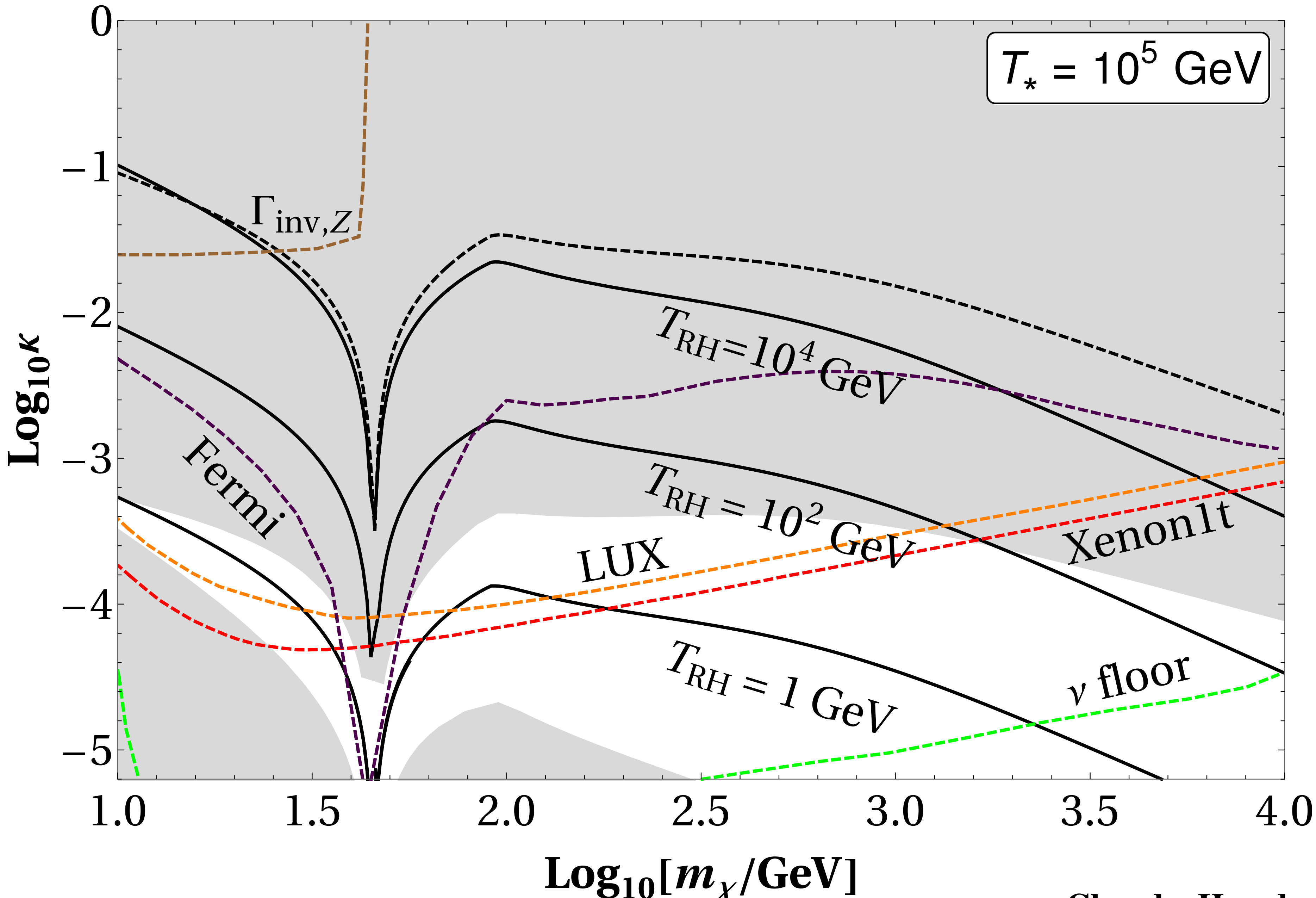
$$\mathcal{L} \supset \frac{1}{\Lambda} H^\dagger H \bar{\chi}\chi \quad \text{define an effective coupling } \kappa = v_0/\Lambda$$



Chanda, Hamdan, & JU [1911.02616]

MDFO via Z Portal

$$\mathcal{L} \supset \frac{g}{4\cos\theta_W}\left(\overline{\chi}\gamma^\mu\left(V_\chi - A_\chi\gamma^5\right)\chi Z_\mu\right) \qquad \text{define} \quad \kappa := V_\chi = A_\chi$$



Chanda, Hamdan, & JU [1911.02616]

Beyond Matter and Radiation Domination

If the early universe is dominated by field evolving as:

$$\rho_\phi(t) = \rho_\phi(t_I)a^{-(4+m)}$$

The **equation of state** for ϕ is $\omega = \frac{p_\phi}{\rho_\phi} = \frac{m+1}{3}$

For m = -1 implies ω=0 and **recovers matter dominated** early universe.

ω different to zero implies **expansion rate** $H \propto T^{2+m/2}$ can impact DM evolution.

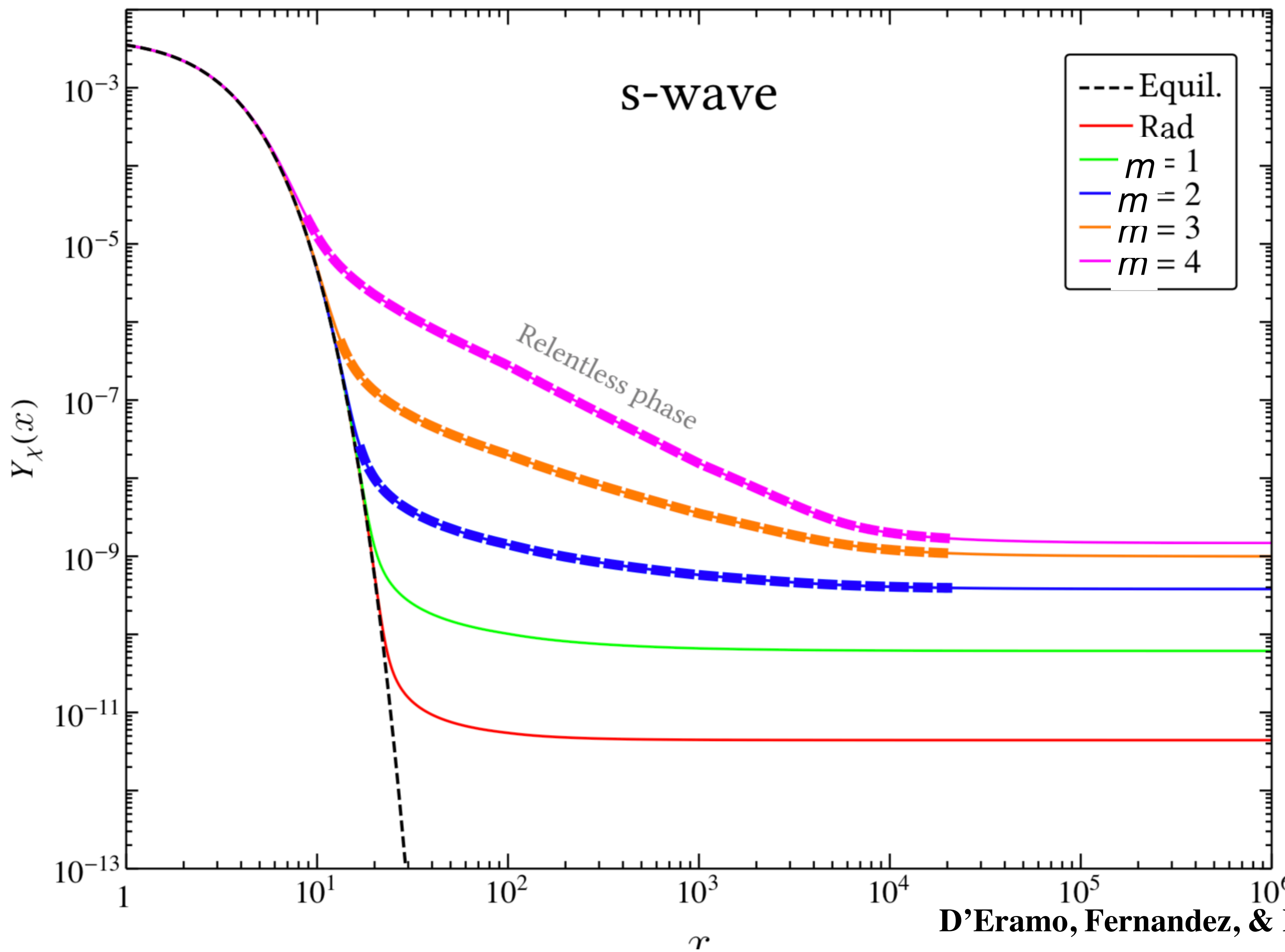
If m>0 (i.e. ω>1) the field will **redshift faster** than radiation - no need for ϕ decays.

Scenario can arise from scalar with potential $V(\phi) = \frac{4-2n}{(4+m)^2 t_I^2} \exp\left[(\phi(t_I) - \phi)\sqrt{m+4}\right]$

D'Eramo, Fernandez, & Profumo [1703.04793]

Beyond Matter and Radiation Domination

Impact on the dark matter relic density for **FO while** $H \propto T^{2+m/2}$

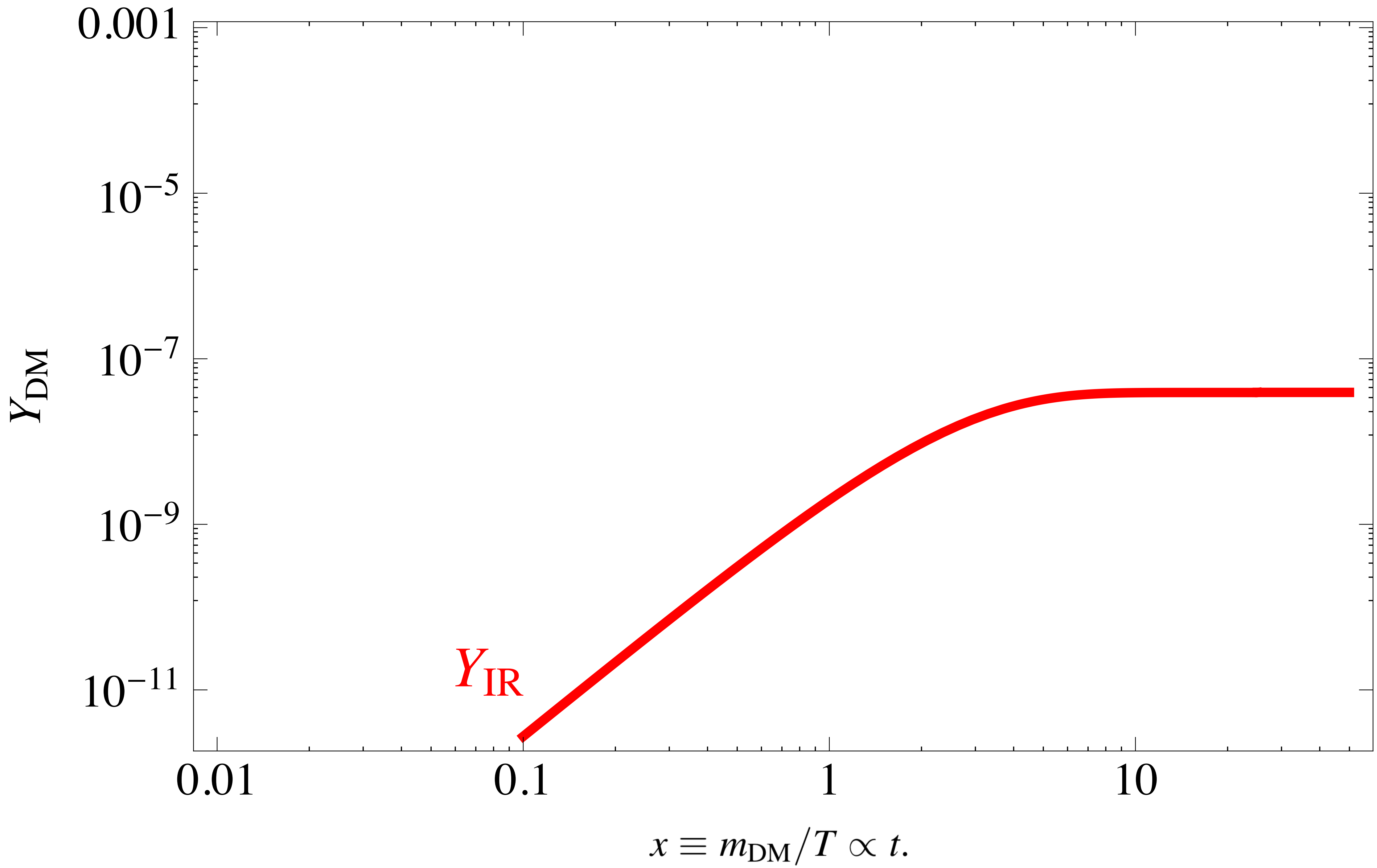


D'Eramo, Fernandez, & Profumo [1703.04793]

III. Dark Matter Freeze-in

Freeze-in

Freeze-in assumes dark matter **initially has negligible abundance.**



Hall, Jedamzik, March-Russell, West [0911.1120]

Freeze-in

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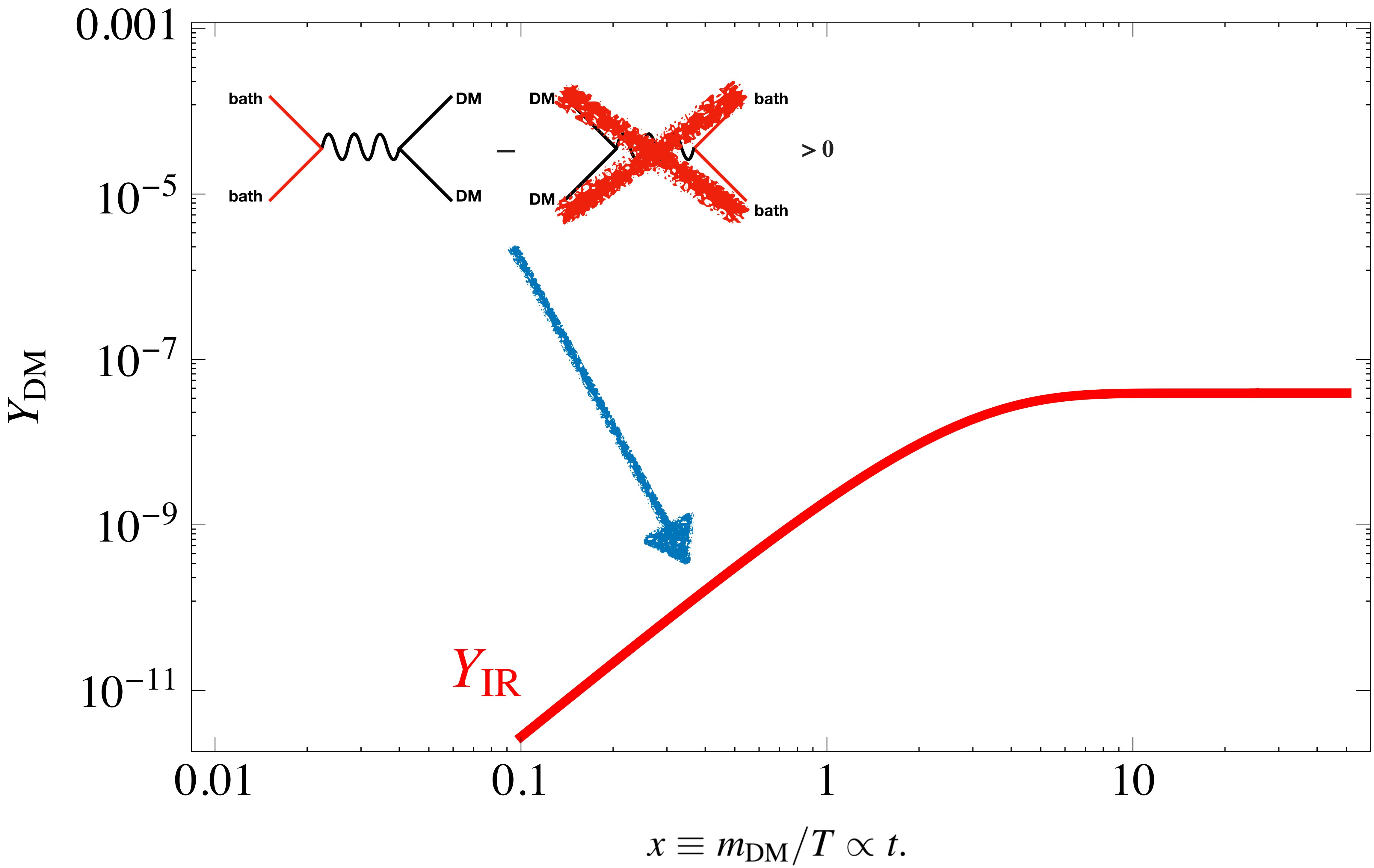

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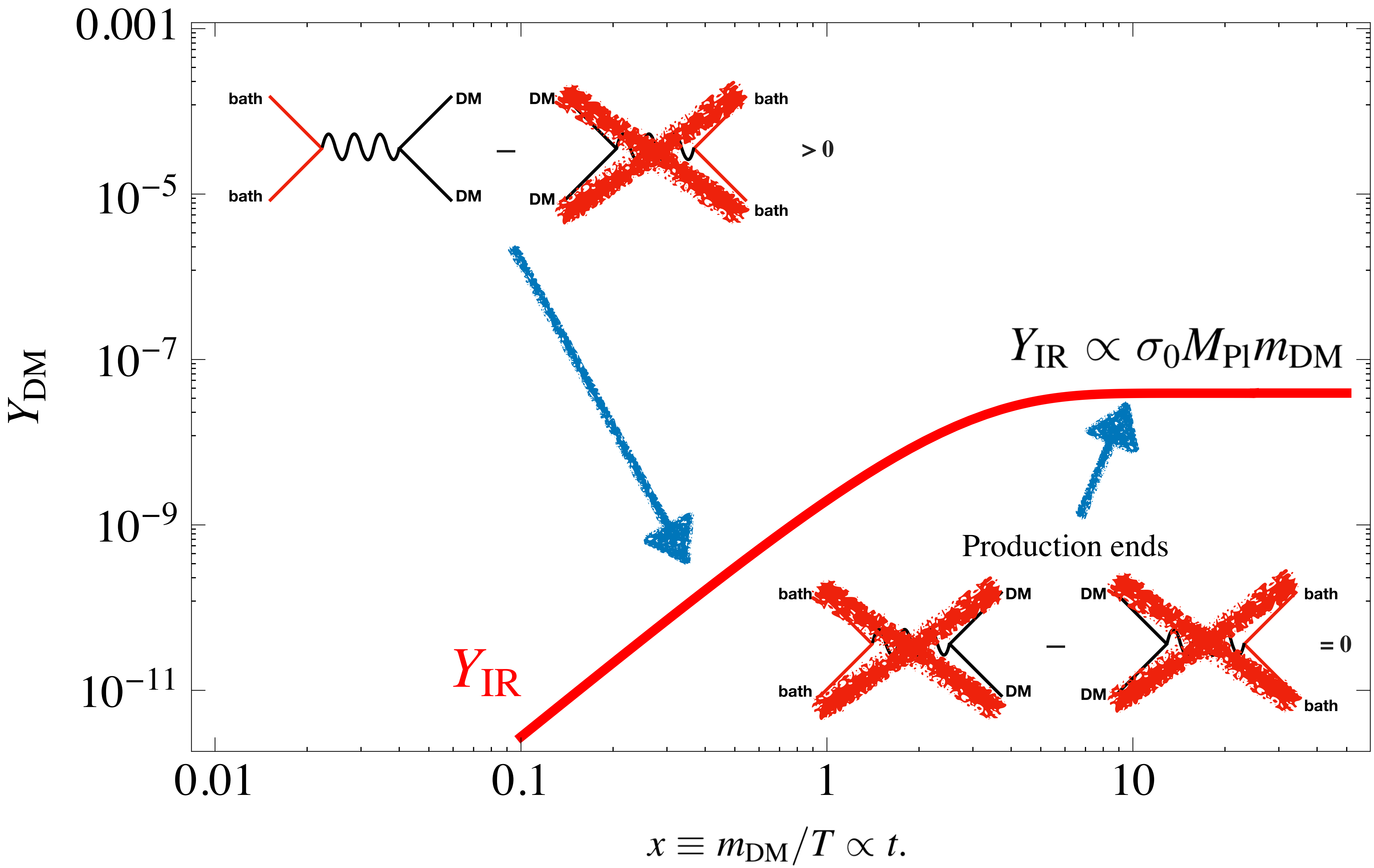
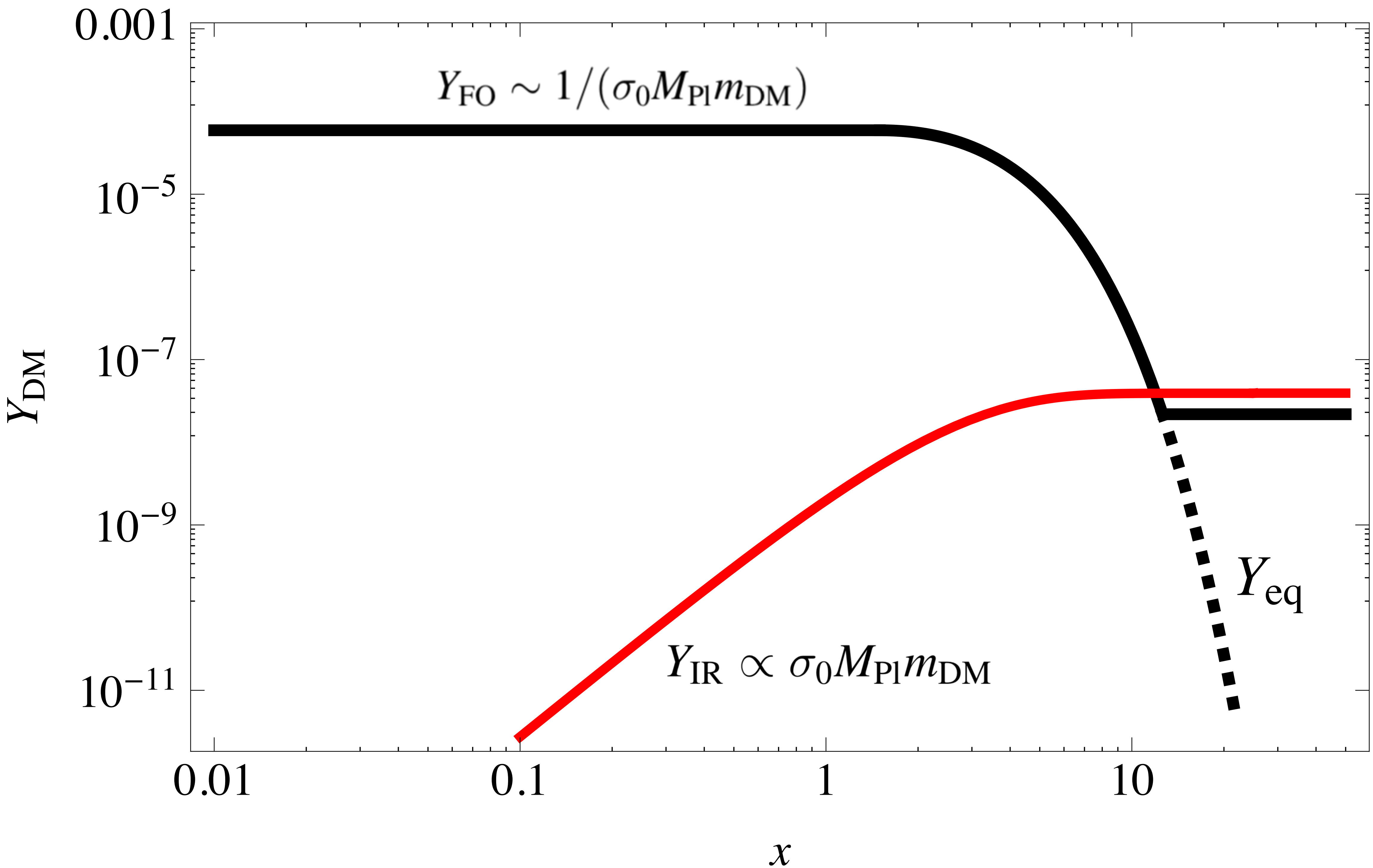
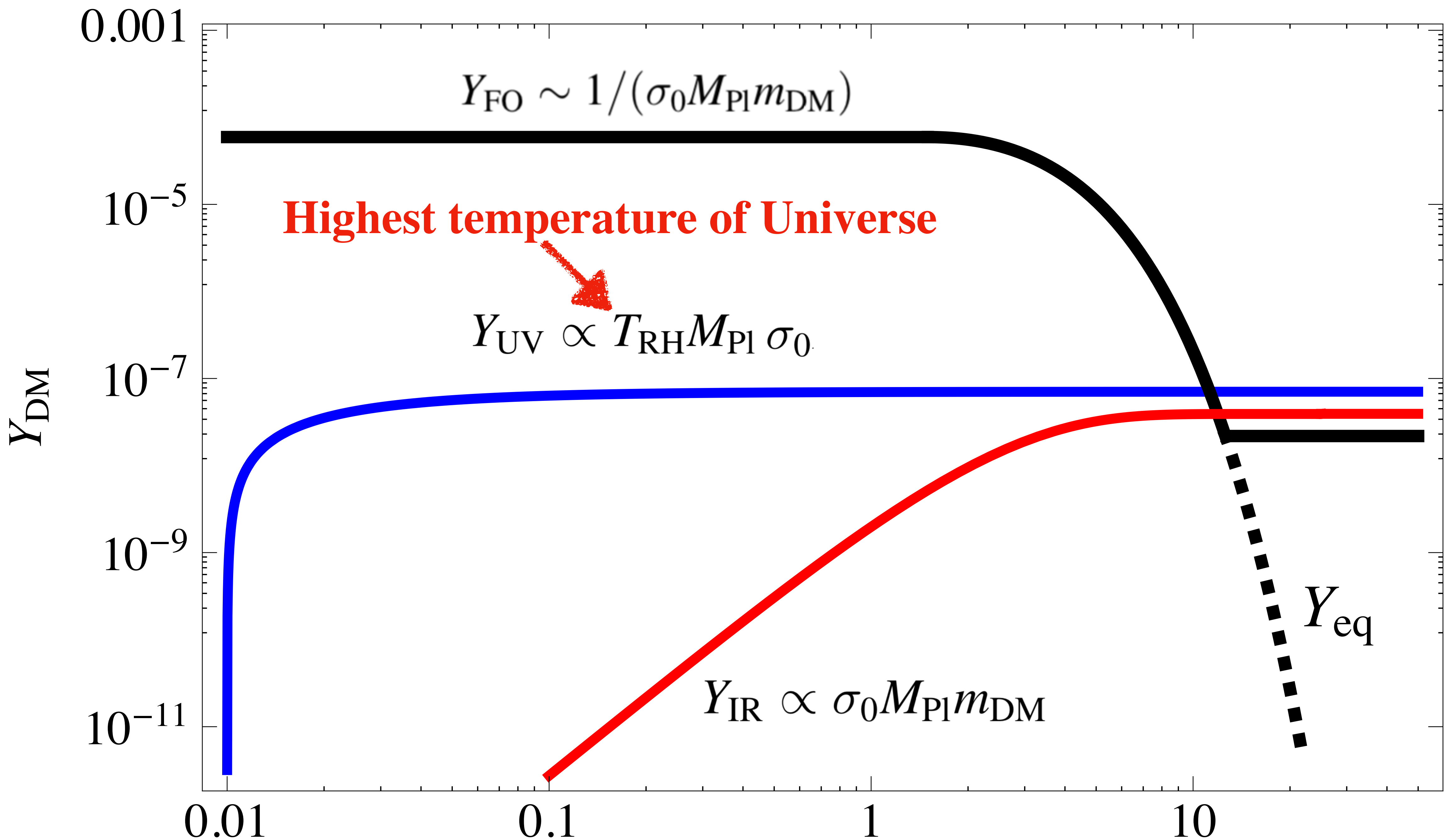


Freeze-in vs Freeze-out



Freeze-in vs Freeze-out



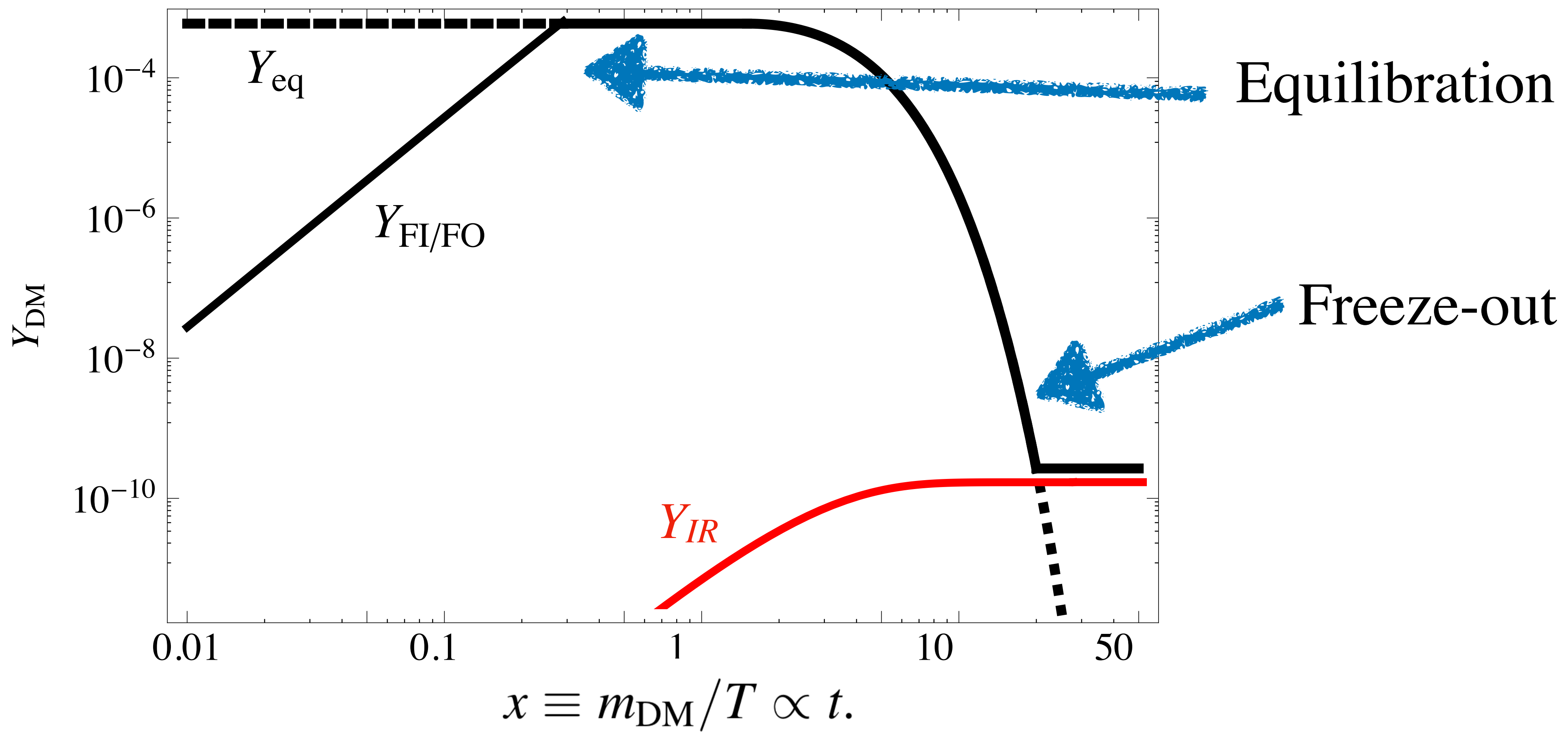
Parameter **depends very different** in Freeze-out, IR Freeze-in & UV Freeze-in.

Hall, Jedamzik, March-Russell, West [0911.1120]

Elahi, Kolda & JU [1410.6157]

Equilibration and FIMPS

If energy exchange is too large, **risk dark matter equilibration** with thermal bath.



Equilibration and FIMPS

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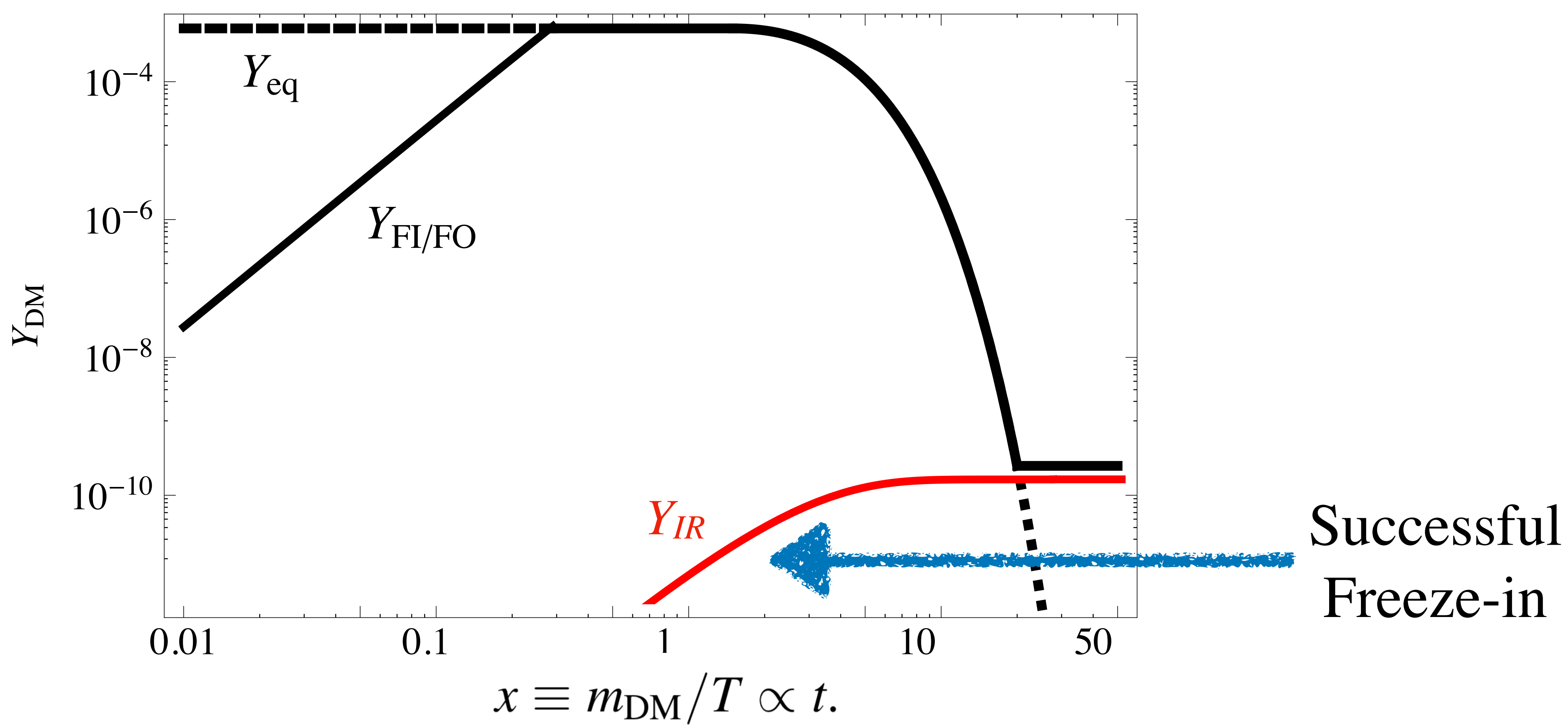


For IR Freeze-in with GeV DM this require couplings: $\lambda \lesssim 10^{-7}$

Avoiding equilibration requires very `feeble' couplings: **FIMP Dark Matter.**

Requires dedicated experiments for light dark matter or long lived states.

IV. UV Freeze-in & Non-Standard Cosmology

Enhancements during UV Freeze-in

UV freeze-in: The production cross section of DM from thermal bath is:

$$\langle \sigma v \rangle \sim \frac{T^n}{\Lambda^{2+n}}$$

Corresponding to Freeze-in operator of **mass dimension** $5 + n/2$.

The **DM abundance** is expected to be

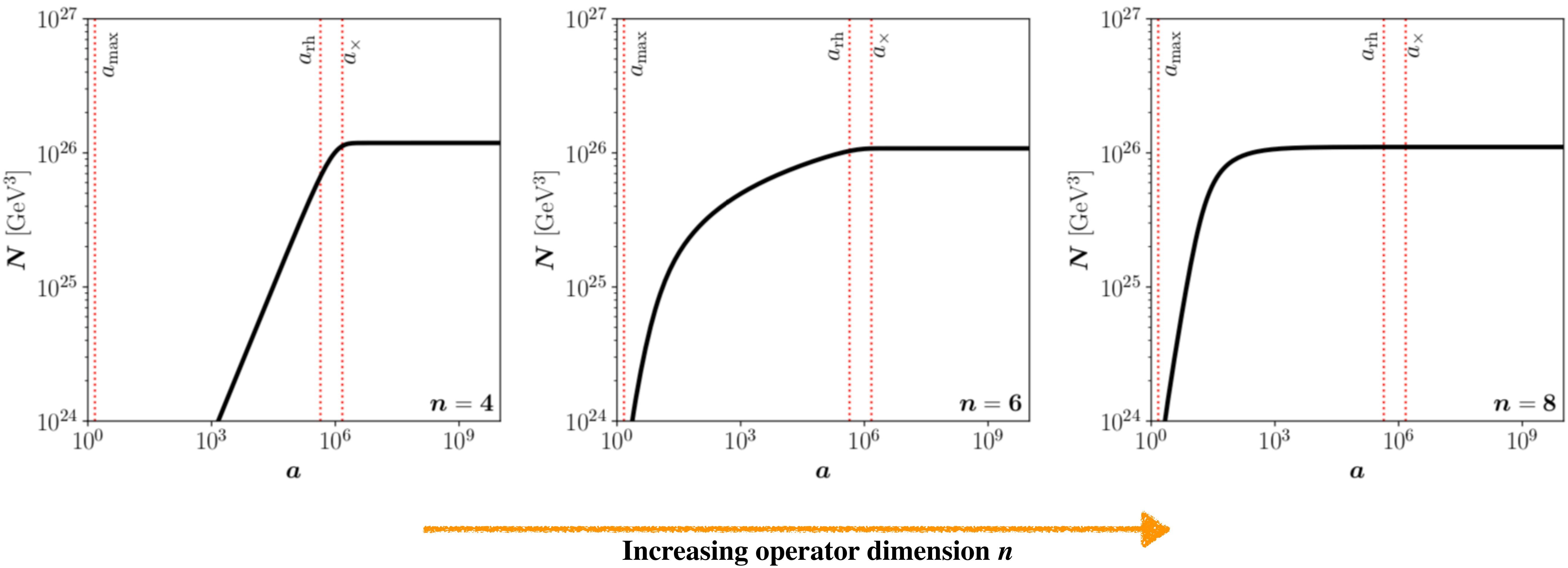
$$Y \sim \int_0^{T_{\rm RH}} \frac{M_{\rm Pl}\, T^n}{\Lambda^{n+2}} \sim \frac{M_{\rm Pl}\, T_{\rm RH}^{n+1}}{\Lambda^{n+2}} \,.$$

$T_{\rm RH}$ is reheat temperature assuming instantaneous decay of inflaton.

Assuming universe **initially matter dominated** before reheating then **for n>6** then DM abundance **enhanced** relative to sudden decay approx.

Garcia, Mambrini, Olive, Peloso, [1709.01549].

Changing operator dimension



For increasing operator dimension the production becomes **more UV dominated**.

Bernal, Elahi, Maldonado, & JU [1909.07992]

Transition from non-standard cosmology

If the early universe is dominated by field ϕ with **equation of state ω**

And the state ϕ is **decaying** to Standard Model radiation then the evolution follows

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi \qquad \frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_\phi\,\rho_\phi$$

It follows the **energy densities evolve** as

$$\rho_\phi(a) = \rho_\phi(a_{\rm in})\left[\frac{a_{\rm in}}{a}\right]^{3(1+\omega)} = 3\,M_{\rm Pl}^2\,H_{\rm in}^2\,\left[\frac{a_{\rm in}}{a}\right]^{3(1+\omega)}$$

$$\rho_R(a) = \frac{6}{5-3\omega}M_{\rm Pl}^2\,H_{\rm in}\,\Gamma_\phi\,\frac{a_{\rm in}^{\frac{3}{2}(1+\omega)}}{a^4}\left[a^{\frac{5-3\omega}{2}} - a_{\rm in}^{\frac{5-3\omega}{2}}\right]$$

where $a = a_{\rm in}$ is the scale factor at some arbitrary initial point, we take the initial condition $\rho_R(a_{\rm in}) = 0$ and thus $H_{\rm in} \equiv H(a_{\rm in}) = \sqrt{\rho_\phi(a_{\rm in})/(3M_{\rm Pl}^2)}$.

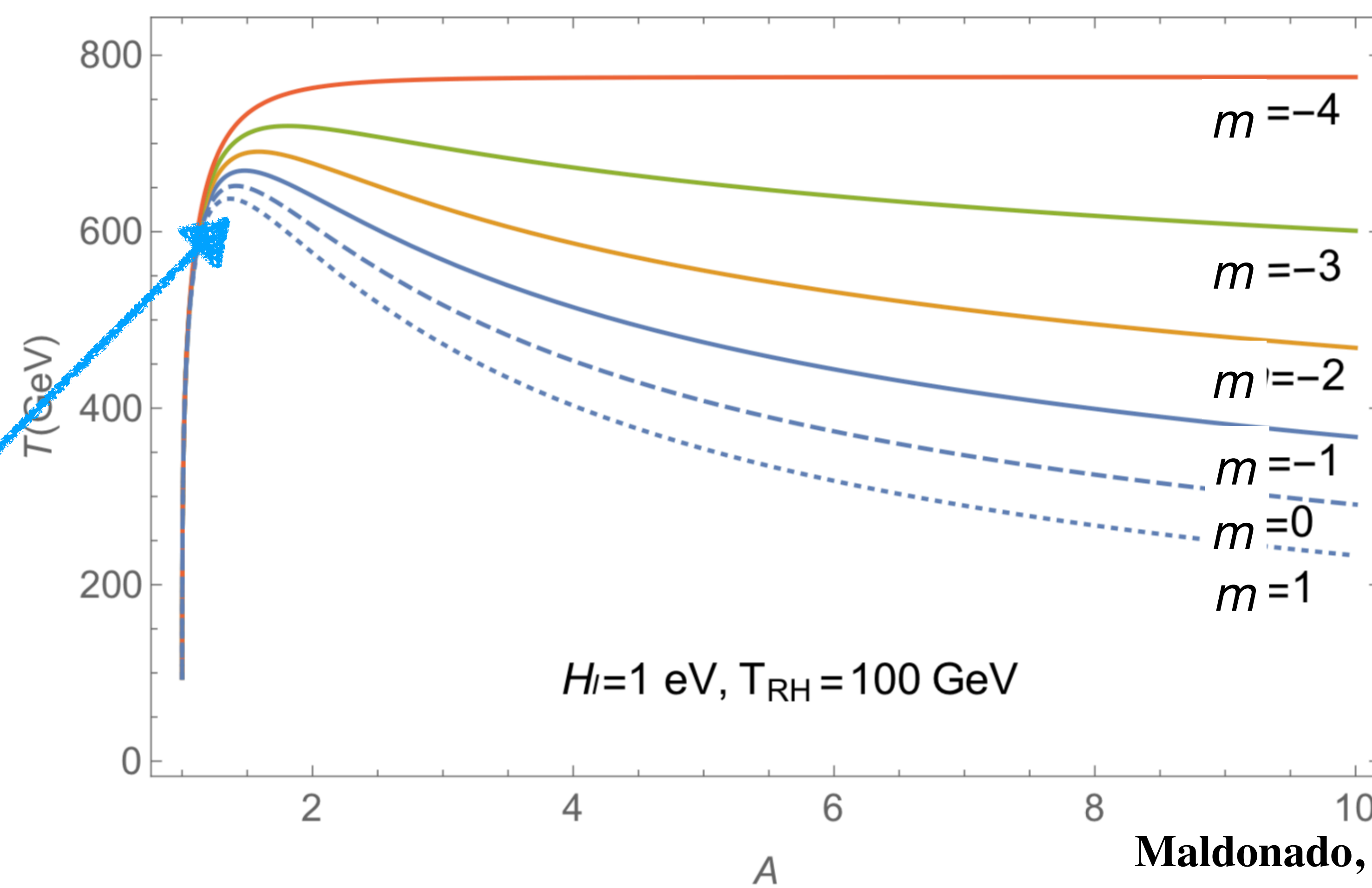
Transition from non-standard cosmology

The **temperature**, related via $\rho_R = \frac{\pi^2 g_*(T)}{30} T^4$, evolves according to

$$T = \left(\frac{45}{4\pi^3}\frac{g_*(T_{\rm RH})}{g_*^2(T)}\right)^{1/8} \left(H_I M_{\rm Pl} T_{\rm RH}^2\right)^{1/4} \left(\frac{A^{-(2+m/2)} - A^{-4}}{2 - m/2}\right)^{-4} \quad \text{where} \quad A \equiv \frac{a}{a_I} = a T_{\rm RH}$$

Define

$T_{\rm max} \geq T_{\rm RH}$



$$\rho_\phi(t) = \rho_\phi(t_I) a^{a+m}$$

Maldonado, & JU [1902.10746]

Dark Matter and Non-Standard Cosmology

This change in cosmological evolution **impacts the dark matter**.

The comoving number density $N \equiv n \times a^3$ evolving according to

$$\frac{dN}{da} = -\frac{\langle \sigma v \rangle}{a^4\, H}\left(N^2 - N_{\rm eq}^2\right)$$

Implying at temperature T

$$N(T) = \frac{8\,\zeta(3)^2\, g^2}{3\pi^4\,(n-n_c)(1+\omega)}\left[\frac{a_{\rm RH}^{3+\omega}}{a_{\rm in}^{1+\omega}}\right]^{\frac{3}{2}} \frac{T_{\rm RH}^{4\frac{3+\omega}{1+\omega}}}{\Lambda^{n+2}\, H_{\rm in}}\left[T_{\rm max}^{n-n_c} - T^{n-n_c}\right]$$

with $n_c \equiv 2 \times \left(\frac{3-\omega}{1+\omega}\right)$

This can be **converted into a yield** $Y(T) = \frac{N(T)}{s(T)\, a^3}$

And integrating to the 'end' of ϕ decays give the **relic abundance**

$$Y(T_{\rm RH}) \sim \frac{1}{(n-n_c)(1+\omega)}\frac{M_{\rm Pl}\, T_{\rm RH}^{\frac{7-\omega}{1+\omega}}}{\Lambda^{n+2}}\left[T_{\rm max}^{n-n_c} - T_{\rm RH}^{n-n_c}\right]$$

Enhancements during UV Freeze-in

For a **fixed ω** then there is a boost relative to sudden decay approx

$$B \simeq \begin{cases} \frac{1}{3}\frac{(1+n)(2+n_c)}{n_c-n} & \text{for } n < n_c\,, \\ \frac{(1+n)\,(2+n)}{3}\ln\frac{T_{\max}}{T_{\rm RH}} & \text{for } n = n_c\,, \\ \frac{1}{3}\frac{(1+n)(2+n_c)}{n-n_c}\left[\frac{T_{\max}}{T_{\rm RH}}\right]^{n-n_c} & \text{for } n > n_c\,. \end{cases}$$

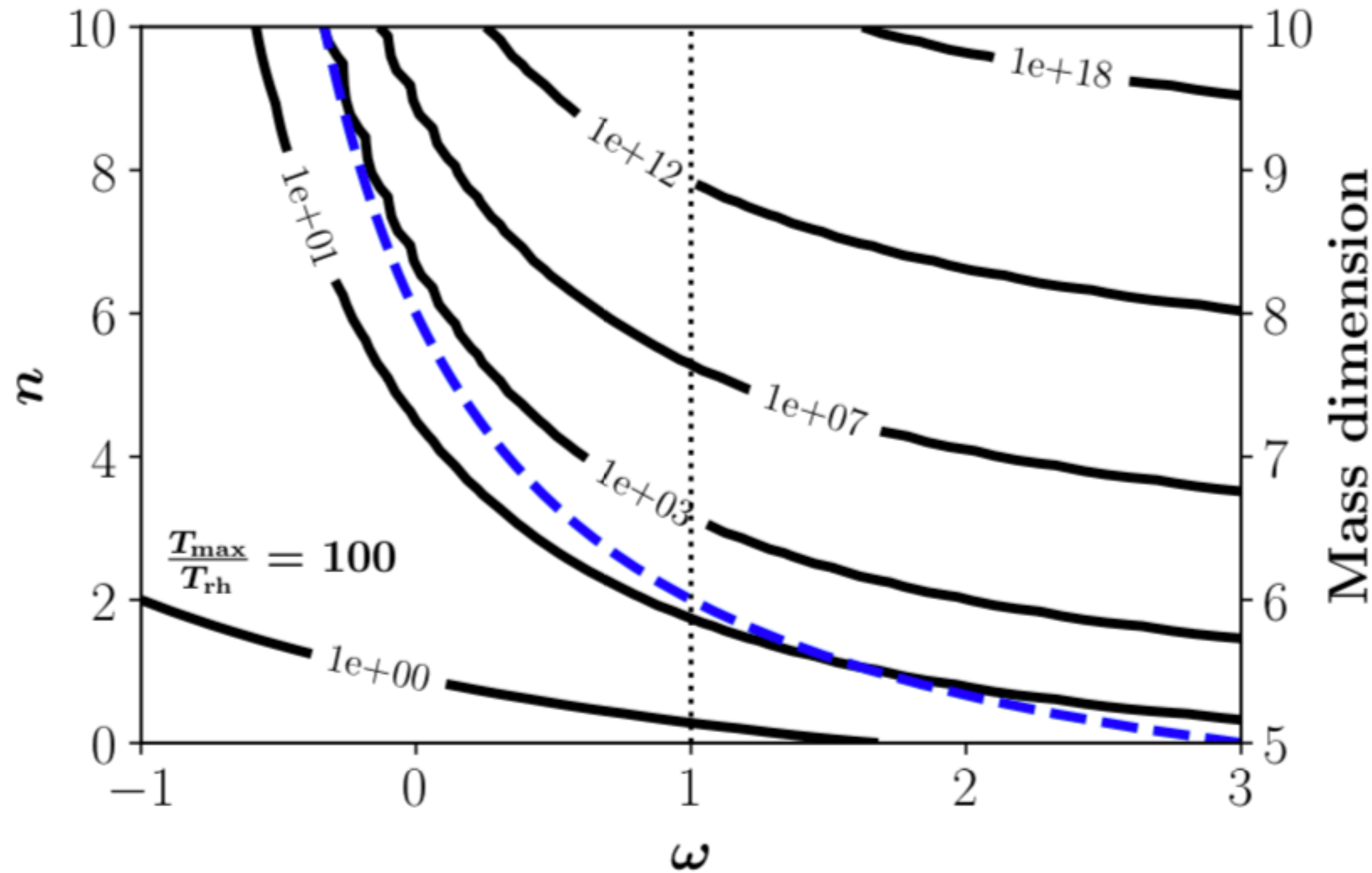
Critical value: $n_c \equiv 2 \times \left(\frac{3-\omega}{1+\omega}\right)$

Recast as a **fixed operator dimension *n*** (varying ω) the boost is

$$B \simeq \begin{cases} \frac{1}{3}\frac{7-\omega_c}{\omega_c-\omega} & \text{for } \omega < \omega_c\,, \\ \frac{8}{3}\frac{7-\omega}{(1+\omega)^2}\ln\frac{T_{\max}}{T_{\rm RH}} & \text{for } \omega = \omega_c\,, \\ \frac{1}{3}\frac{7-\omega_c}{\omega-\omega_c}\left[\frac{T_{\max}}{T_{\rm RH}}\right]^{\frac{8(\omega-\omega_c)}{(1+\omega)(1+\omega_c)}} & \text{for } \omega > \omega_c\,, \end{cases}$$

Critical value: $\omega_c \equiv \frac{6-n}{2+n}$

Boosting to large abundance



Useful for motivated dark matter candidates which are **underproduced**.
For example gravitino dark matter in high scale supersymmetry scenarios.

Bernal, Elahi, Maldonado, & JU [1909.07992]

Conclusion

- **Cosmological events** and can drastically alter expectations for DM.
- Dilution permit correct relic density for **heavier DM** or **smaller couplings**.
- This can **revive the Higgs portal** (and other excluded classic models).
- Conversely, **underproduced DM** can be enhanced via reheating effects.
- Non standard cosmology occurs in many **motivated BSM scenarios**.

Thank you.